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THE PROBLEM OF SPACE FLIGHT WORTH ANALYSIS

by G. R. WOODCOCK
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George C. Marshall Space Flight Center, Huntsville, Alabama

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ABSTRACT

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Possible approaches are discussed, the method of analysis used is presented, and observations concerning the results are given.

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FUTURE PROJECTS OFFICE
RESEARCH AND DEVELOPMENT OPERATIONS

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DEFINITIONS

Program	a combination of individual space flight projects established to attain broad national or international objectives.
Project	a space flight undertaking with a particular goal; consists of one or more flight mission attempts to attain the established goal.
Program Yield	the total produced measurable output of a program in terms of transportation indices, cost effectiveness factors, and milestones reached.
Yield Measurements	individual yardsticks, which can be well defined measures of accomplishments related to mass, time, man-round-trips, performance, information rates, etc.
Program Worth	an indication of the degree (in percent) a program is expected to achieve the specified objectives; is calculated as the sum of the partial worth related to individual objectives specified.

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THE PROBLEM OF SPACE FLIGHT WORTH ANALYSIS

SUMMARY

This report discusses some of the problems of space flight worth analysis and presents one approach explored by the author. Space flight worth analysis is an attempt to determine how much effort we should expend in space, and within this limitation, determine what are the best projects and programs. The input to the analysis is estimated technical capability versus time.

Possible approaches are discussed, the method of analysis used is presented, and observations concerning the results are given.

SECTION I. INTRODUCTION

The dominant question in future projects planning for space flight activities has always been: What technically can we do in space, and when? However, with the emergence of the Apollo project, the nation's technical capability in space is expanding very rapidly to the point that we will soon be technically capable of much more than we could possibly afford to do; therefore, the question of what we can do in space is now interrelated with two other questions: (1) How much effort can we or should we expend in space? (2) Within this limitation, which are the best projects and programs? Attempts to answer these two questions we call "Space Flight Worth Analysis," which uses estimated technical capability vs. time as an input.

The purpose of this report is to discuss some of the problems of space flight worth analysis, and to present one approach that has been explored by the author. Possible approaches to the problem are discussed, the method used in the author's analysis is presented, and observations are made concerning the results.*

* The opinions discussed are those of the author and not necessarily those of the National Aeronautics and Space Administration.

SECTION II. DISCUSSION OF POSSIBLE APPROACHES

Worth analysis is a systematic means of determining the worth returned as a result of engaging in a given activity. Ordinarily, worth analysis measures delivered value in terms of explicit and well understood parameters, such as dollars or the most of some definite item delivered per dollar. In space flight worth analysis we are faced with more difficult problems. We can certainly try to maximize worth delivered per dollar, but how do we measure worth? A frequently used parameter is dollars per pound in orbit, which one of course wishes to minimize; but, this is really cost effectiveness analysis and not worth analysis. It does not answer the fundamental questions asked above, and it does not provide for the comparison of the worth of pounds of payload in orbit with the worth of a Mars flyby mission, or man-years on the Moon.

Any of the cost effectiveness parameters, such as dollars per pound in orbit or dollars per man-year on the Moon, etc., can be made smaller and, therefore, more attractive by increasing the total expenditure level of a program. It is clear that cost effectiveness parameters by themselves will not determine the desired expenditure level. So we are led to the question: What are the real goals of space flight activities? The Future Projects Office of MSFC formulated a list of 5 objectives of space flight, and another more specific list of 20. The list of 20 is not necessarily more inclusive than the list of 5, but a great deal more specific. These lists are tabulated below in Tables I and II. Both tables are listed in order of importance and weighting factors are shown to indicate the relative importance of each item.

TABLE I. FIVE OBJECTIVES OF SPACE FLIGHT

Rank		Weight Factor
1	Stimulation of the National Economy and Welfare	35
2	National Security Resulting from Military Capability	20
3	National Prestige and Political Advantage	20
4	Advancement in Scientific and Technical Knowledge	15
5	Development of Technology Applicable to Future Transportation Systems	10

TABLE II. TWENTY WEIGHTED OBJECTIVES OF THE NATIONAL SPACE PROGRAM

Rank		Weight Factor
1	Achieve and preserve U. S. International leadership (by demonstration of actual space flight capabilities and scientific accomplishments).	8.2
2	Utilize new knowledge and technologies, obtained from space flight activities, for the benefit of mankind (such as weather forecasting, communications, navigation, medical applications, materials, productivity techniques, etc.).	8.0
3	Space activities will provide more insight into, and understanding of, the fundamental physical nature of the universe and of life itself.	6.2
4	Develop a technological and industrial base, which can support national security needs for manned space systems with relatively short leadtime.	6.1
5	Raise the level of general knowledge in many areas of human activities, and provide the incentive for improved education.	5.9
6	Promote international cooperation for peaceful purposes (thus reduce world tension and strengthen the cause of peace).	5.8
7	Stimulate the nation as a whole, by engaging in large-scale space flight development and operations (thus providing a sense of purpose and excitement for the nation, as well as creative opportunities).	5.7
8	Stimulate the national economy by providing incentives for new investments, to raise employment.	5.6
9	Demonstrate operational feasibility and utility of space systems, which may be applied to national security requirements.	5.5

TABLE II. TWENTY WEIGHTED OBJECTIVES OF THE NATIONAL SPACE PROGRAM (Cont'd)

Rank		Weight Factor
10	Space activities will result in a major expansion of knowledge about the terrestrial and space environment, which is required for the development of aeronautical and space transportation systems.	5.3
11	Strengthen the educational facilities and build direct relationships for scientific experiments and training of scientists and engineers.	5.2
12	Maintain and expand industrial base continuity, including contracting and management practices (thus enabling the U.S. to cope with complex problems and systems when required).	4.9
13	Space activities will result in the availability of dependable and efficient manned space transportation systems for a wide range of potential applications.	4.8
14	Strengthen, within the government, the capability to manage the development of complex systems, and find solutions to complex problems (thus strengthening and preparing the government for times of crisis).	4.3
15	Provide the capability of overt inspection to enforce arms control agreements, while providing an alternate chennel for resources utilization during the adjustment period of the national economy.	4.1
16	Space vehicle development will result in a capability to transport personnel and cargo very rapidly to any point on this globe.	4.0
17	Development of new policies, procedures and systems to make most effective use of scarce special skills, capabilities, and other resources (thus enhancing the competitive position of the U.S. in the area of foreign trade).	3.0

TABLE II. TWENTY WEIGHTED OBJECTIVES OF THE NATIONAL SPACE PROGRAM (Cont'd)

Rank		Weight Factor
18	Space vehicle development and operation will greatly improve aeronautical transportation systems.	2.8
19	Space activities will result in the availability of dependable and efficient unmanned space transportation systems.	2.6
20	Exploit extraterrestrial resources for the benefit of mankind.	2.0

It should be made clear at the outset that because of the intangible nature of the worth associated with space flight, the selection of one space exploration program as superior to another or the synthesis of an optimum program on the basis of such an intangible parameter as "worth" is greatly a matter of opinion. Although the methodology to be discussed later involves the use of a digital computer machine program for rapid processing of the data, this machine program does not make any magical decisions nor does it change the subjective nature of the analysis. There is, of course, no absolute way in which to decide the relative importance of all of these items. The ranking and relative importance of the objectives given in Tables I and II were determined by a process of opinion sampling in the Future Projects Office and other elements of MSFC. The subject of opinion sampling deserves some discussion.

Is opinion sampling an acceptable way to determine relative importances of such things as the listed objectives? If so, whose opinions shall be sampled? In answer to the first question, it is the writer's position that there is no other authority accessible to us to which we can appeal to establish relative importances. In this problem, we are unfortunately not dealing with physical laws, or anything that can be measured in physical units. Even in such presumably definite matters as national security, there is still a variance of opinion. Although almost everyone would agree that national security is important, we may be sure that individuals could be found who would not think so, and one can certainly get plenty of arguments as to whether or not any particular space activity is important in terms of national security.

The second part of the question, i.e., whose opinion shall be solicited, is more difficult to answer. This question must be considered in the context of the ultimate use that will be made of the results of the worth analysis. At this point, we begin to become inextricably entangled in the problems of justification for space and how much space activity the country as a whole is willing to support. It is quite clear that decisions on these problems will be made by the Executive and Legislative Branches of the National Government, since they request and appropriate the funds without which there is no space program. These members of government will be affected to some degree by public opinion on the matter, since they are ultimately responsible to the people by whom they are elected to office. Should we then solicit from legislators and the public, their opinions to be used in the worth analysis? The answer at this point is no. Although legislators and the public are certainly qualified to judge the importance of the various objectives tabulated in the previous table, they are probably not well qualified to evaluate how various space activities relate to these objectives. It should be pointed out, however, that the lists of objectives previously given were developed by expanding on the NASA missions stated in the Space Act of 1958.

The next logical step in this line of reasoning is to conclude that if NASA wishes to continue with an active space program, it had better get busy educating the public and our law makers as to the significance of space. To be able to do this, we at NASA must first be able to educate ourselves, and it is this more immediate objective for which worth analysis should first be used. Therefore, at present it is adequate to use the opinions of NASA management, although there is little doubt that these opinions will be biased in favor of a strong space program.

At this point, we have satisfied ourselves that we have a representative list of objectives that a space program should satisfy, and we have a usable body of opinions with which to rate the objectives. Unfortunately, however, the outputs of space programs are not directly measurable in terms of the listed objectives, and in cases where they may seem to be, numerical measurability does not exist. The measurable output of a space program is in terms of useful payload in orbit and to various destinations in space, and man-years in various space activities. Further outputs that might be considered are specifically useful technical developments such as vehicles or spacecraft systems and the accumulation of valuable technical experience, such as the number of space launches or number of man-round trips to orbit. These things are numerically measurable and cost estimates may be made for their accomplishments to various degrees. How they relate to the previously discussed objectives is a matter of opinion.

In order to make numerically relative comparisons between various space programs, we must have numerical relationships of some kind between the directly measurable yields from space activity and the unmeasurable objectives. Constructions of the relationships or correlations will necessarily, to some degree, be controlled by the opinions of the individual or group developing the worth analysis method, but may also, to some degree, be made a matter for further opinion sampling. Typical of the cases where these relationships are determined almost exclusively by the analyst is the establishment of explicit worth estimating equations. Such methods have been employed in the Future Projects Office activities. In order to obtain a comparison, the approach to be described in detail here was formulated, in which it was desired to have sampled opinions play a maximum role. There are very good arguments for either general type of approach; these will be discussed further.

SECTION III. METHOD OF ANALYSIS

The method of analysis was set up with the objective in mind to be able, by use of a machine program, to reduce the selection and optimization process from a "seat of the pants" and "stab in the dark" affair to a modest size set of discrete judgments involving sufficiently few parameters so that the major features affecting each individual judgment can be relatively easily grasped. If this is not done, the individual making the decisions would be faced with an incomprehensible conglomeration of data, variables, permutations, and detail choices.

In brief, the method consisted of setting up a matrix of correlation between measurable yields and the previously discussed objectives. For purposes of development of the method, the shorter list of five objectives was used. The matrix, which contained 15 yield items, is shown in Figure 1. Those people whose opinions were solicited were requested to fill in the matrix with numbers, each of which represented (in their opinion), in a relative way, the degree by which a particular yield satisfied a particular objective. The other factor which must be considered in a worth analysis is cost. In this particular analysis, cost was measured strictly in terms of estimated program costs in dollars. Other kinds of cost, such as investment of technical manpower, could be considered; however, the scope of the space programs to be analyzed did not appear sufficiently large to be an undue strain on the total technological capability of the nation. Dollars invested in space exploration, on the other hand, receive a great deal of consideration from many people.

OBJECTIVES ↓ / YIELDS →	KILOPOUNDS USEFUL PAYLOAD IN EARTH ORBIT	SCIENTIFIC MAN-WEEKS IN EARTH ORBIT	MISSION SUPPORT MAN-WEEKS IN EARTH ORBIT	KILOPOUNDS USEFUL PAYLOAD TO THE MOON	MAN-WEEKS ON THE MOON	KILOPOUNDS OF USEFUL PAYLOAD IN CIS-PLANETARY SPACE	KILOPOUNDS OF USEFUL PAYLOAD ON THE PLANETS	MAN-YEARS IN VICINITY OF PLANETS	MAN-WEEKS ON PLANETS	DEVELOPMENT OF REUSABLE ORBITAL TRANSPORT	DEVELOPMENT OF POST-SATURN	DEVELOPMENT OF GROT	DEVELOPMENT OF SCN NUC FERRY	DEVELOPMENT OF NUCLEAR PULSE FERRY	DEVELOPMENT OF SPACECRAFT SYSTEMS
KEY YEARS →	1972	1974	1975	1975	1976	1976	1979	1980	1987						
POLITICS, PRESTIGE	37.5	63	35.4	66.1	97.8	37.5	88.5	105.2	147.2	48.4	60	55	51.8	-9.8	33.3
NAT'L SECURITY	154.4	128.7	184.1	51.4	79.6	5.6	1.1	5.5	11	115.4	43.2	52.6	26.3	59.6	51.4
GENERAL WELFARE	145.3	161.4	93.2	44.1	55.5	45.2	36.8	44.5	44.5	82.8	45.7	70.3	45.7	26.6	58.9
SCIENCE AND TECHNOLOGY	54.6	83	31.3	47.1	71.9	70.4	62.8	104	169.1	45.8	47.8	53	42.8	39.9	61.5
TRANSPORTATION SYSTEMS	33.5	32	45.2	25.7	29.1	34.9	34.9	31.6	37.7	231.5	97.6	213.3	68.2	50.1	34.6

FIGURE 1. OBJECTIVE-YIELD CORRELATION MATRIX

A final feature which might be discussed before going into details, is the use of a learning curve. As we have more and more activities and experience in a particular space environment, we will learn more about the environment and what its potentialities are and the value of continuing that activity will be somewhat decreased. To express this numerically, a function of the learning curve type was chosen. This kind of function has seen wide application in expressing decreases in manufacturing costs of hardware, etc. The nature of this function is that the second unit is worth a given fraction, say 90 percent, of the first unit, then the fourth unit is worth 90 percent of the second, the eighth worth 90 percent of the fourth, etc. In the example just noted, the learning curve has a 90 percent slope. In the worth analysis described here, learning curve slopes were selectable parameters and a different learning curve slope could be selected for each yield item if desired. If it were preferred not to use the learning curve slope at all, a slope of zero could be used.

The following nomenclature and symbols are used in exposition of the mathematical methodology used for the worth analysis:

NOMENCLATURE

$[C]$	Cost matrix
c	Elements of cost matrix
R	Relative worth (worth per dollar)
$[V_c]$	Correlation matrix (Figure 1)
v	Elements of $[V_c]$
$[W_o]$	Matrix of program objective weighting factors
w	Elements of $[W_o]$
$[W_o^p]$	Modified version of $[W_o]$; politically oriented (see text)
$[W'];[W_s]$	Intermediate matrices used in computing worth matrix
$[W'^p];[W_s^p]$	Politically oriented version of $[W']$ and $[W_s]$ (see text)
$[Y]$	Yield matrix
$[Y']$	Adjusted yield matrix
y	Elements of yield matrix
y'	Elements of adjusted yield matrix
$[\ ]$	Indicates a matrix
$[\ ]\ [\ ]$	Indicates matrix multiplication

GREEK SYMBOLS

λ	Learning curve slope
$[\Omega]$	Worth matrix
ω	Elements of $[\Omega]$

SUBSCRIPTS

i	Index of objectives
j	Index of yields
k	General index
l	Index of program years

The model will accept up to 25 objectives, 20 yield items, and a 25-year program. Some increase in capacity could be obtained with very little effort.

The following are needed as inputs:

1. Number of objectives and yield items; length of program, initial year.

2. Name of each objective item; whether it is political in nature; its weighting factor.

3. Name of each yield item; year before which it should be first accomplished to get political and prestige value; learning curve slope.

4. Correlation matrix.

5. Yield matrix.

6. Cost matrix.

7. Title of run.

The yield matrix is of the form,

$$[Y] = \begin{array}{c} \longleftarrow \text{yields} \longrightarrow \\ \begin{bmatrix} y_{11} & y_{12} \cdots\cdots\cdots y_{1j} \\ y_{21} & \cdots\cdots\cdots\cdots\cdots \\ y_{l1} & \cdots\cdots\cdots\cdots y_{lj} \end{bmatrix} \end{array} \begin{array}{c} \uparrow \\ \text{years} \\ \downarrow \end{array} \qquad (1)$$

where y_{11} is the yield category "1" for year 1 (the first year in the program); j ranges from 1 to the number of yield items and l ranges from 1 to the number of years in the program.

The learning curve is defined as follows: The adjusted value of the kth unit of yield, y'_k, is equal to the unadjusted value diminished by the ratio $(\Sigma_y)^{1+\lambda}/\Sigma_y$ where λ is the learning curve slope, normally negative. The adjusted value of all yield up to and including the kth unit is

$$Y'_k = \int_0^{y_k} y^\lambda dy = \frac{y_k^{1+\lambda}}{1+\lambda} \qquad (2)$$

The adjusted value of the yield delivered in a given year is, therefore,

$$y_{lj} = \frac{y_{lj}^{1+\lambda} - y_{l-1,j}^{1+\lambda}}{1+\lambda} \qquad (3)$$

This relation is used to construct an adjusted yield matrix, $[Y']$.

The total yield in a given category over the program is, of course

$$y_s = \sum_l y_{lj} \qquad (4)$$

$$y'_s = \sum_l y'_{lj} \qquad (5)$$

Both unadjusted and adjusted values are of interest. Elements of the cost matrix have a one-to-one correspondence with elements of the yield matrix; i. e. , each element is the amount spent achieving a given yield in a given year.

$$\begin{array}{cc} & \longleftarrow \text{yields} \longrightarrow \\ [C] = & \begin{bmatrix} C_{11} & C_{12} \cdots\cdots & C_{1j} \\ C_{21} & \cdots\cdots & \cdots \\ \cdots & \cdots\cdots & \cdots \\ C_{l1} & \cdots\cdots & C_{lj} \end{bmatrix} \end{array} \updownarrow \text{years} \qquad (6)$$

Total cost per year is

$$C_1 = \sum_j C_{1j} \, . \tag{7}$$

Weighting factors for the objectives form a row matrix,

$$\begin{array}{cc} & \xleftarrow{\quad} \text{objectives} \xrightarrow{\quad} \\ [W_o] = & [w_1 \quad w_2 \; \cdots\cdots\cdots\cdots \; w_i] \end{array} \tag{8}$$

where i ranges from 1 to the number of objectives. The correlation matrix is of the form,

$$\begin{array}{ccc} & \xleftarrow{\quad} \text{yields} \xrightarrow{\quad} & \\ [V_c] = & \begin{bmatrix} V_{11} & V_{12} \cdots\cdots\cdots\cdots & V_{1j} \\ V_{21} & \cdots\cdots\cdots\cdots\cdots & \cdots \\ \cdots & \cdots\cdots\cdots\cdots\cdots & \cdots \\ V_{i1} & \cdots\cdots\cdots\cdots\cdots & V_{ij} \end{bmatrix} & \updownarrow \text{ objectives} \end{array} \tag{9}$$

It is assumed that the worth delivered in a given year for a given yield category and a given objective can be computed by multiplying the adjusted yield by the weighting factor for that objective, and then by the appropriate value in the correlation matrix. In other words, if we wish to know the worth for yield category 3 in the fourth year for objective 2, we have

$$w_{2,3,4} = y'_{43} \, v_{23} \, w_2 \tag{10}$$

Summing over objectives gives the worth for that year and that yield item. In matrix form:

$$\text{Step One:} \quad [W'] = [W_o][V_c] \tag{11}$$

where the elements of $[W']$ are w'_{ij} .

A new row matrix, $[W_s]$, is generated by $w''_j = \sum_i w'_{ij}$. (12)

The worth matrix is then formed by

$$[\Omega] = [W_s][Y'] \tag{13}$$

where elements of $[\Omega]$ are ω_{lj}.

Three results, in terms of relative worth, are of interest, where relative worth is per dollar: (Note the one-to-one correspondence between elements of $[C]$ and $[\Omega]$).

1. Relative worth per year, $R_l = \dfrac{\sum_j \omega_{lj}}{\sum_j c_{lj}}$ (14)

2. Relative worth for each yield item at program end

$$R_j = \frac{\sum_l \omega_{lj}}{\sum_l c_{lj}} \tag{15}$$

3. Overall relative worth for the program.

$$R = \frac{\sum_l \sum_j \omega_{lj}}{\sum_l \sum_j c_{lj}} \tag{16}$$

A modification to the above basic model was made to give consideration to time of achievement of milestones (first yield in each yield category). First, a special matrix $[W_o^p]$ was constructed in which the elements W_i were zero if the corresponding objective <u>was not</u> political. For example, if only the first objective was political, $[W_o^p]$ would be $[W_1\ 0\ 0\ \ldots.\ 0]$. Equations (11) and (12) were then used with $[W_o^p]$ in place of $[W_o]$ to form $[W'^2]$ and $[W_s^p]$. This was repeated with a special matrix $[W_o^o]$ for which the elements w_i were zero <u>if</u> the corresponding objective <u>was</u> political; resulting in $[W'^0]$ and $[W_s^o]$.

Next, the adjusted yield matrix [Y'] was modified according to the following rule, to form $[Y'^{p}]$:

1. If first yield was achieved before or during the key year entered in item (3) of the inputs, this yield value was multiplied by 10.

2. For each year thereafter, or after the key year, if the first yield was not achieved by the key year, yield was divided by 2.

3. If no key year was entered, yields in that category were not changed.

The following matrix of 3 yield categories is given as an example:

Category 1	Category 2	Category 3	
1970	1972	None	Key Year
			Program Year
0	0	0	1967
$10(y_{21})$	0	0	1968
$\frac{1}{2}y_{31}$	0	0	1970
$\frac{1}{4}y_{41}$	0	y_{43}	1971
$\frac{1}{8}y_{51}$	0	y_{53}	1972
$\frac{1}{16}y_{61}$	$\frac{0}{2}$	y_{63}	1973
$\frac{1}{32}y_{71}$	$\frac{1}{4}y_{72}$	y_{73}	1974
$\frac{1}{64}y_{81}$	$\frac{1}{8}y_{82}$	y_{83}	1975
$\frac{1}{128}y_{91}$	$\frac{1}{16}y_{92}$	y_{93}	1976

Two worth matrices were then formed:

$$[\Omega^p] = [W_s^p][Y'^p] \tag{17}$$

$$[\Omega^o] = [W_s^o][Y'] \tag{18}$$

Equations (14), (15), (16) then become

$$R_1 = \frac{\sum_j \omega_{1j}^o + \sum_j \omega_{1j}^p}{\sum_j c_{1j}} \tag{19}$$

and so forth. Note that if no key years are entered for any of the yield categories, the two versions of the model are identical.

SECTION IV. DISCUSSION OF RESULTS

A. ANALYSIS OF ALTERNATIVE PROGRAMS

Six typical programs were analyzed with this Worth Analysis Model. A detailed description of each of these programs may be found in NASA Technical Memorandum titled, "A Model Simulating Alternative Space Programs," by the Technical Staff, Future Projects Office, now in preparation. Costs of the programs were estimated by the Program Analysis and Control group of Future Projects Office. The Appendix of this paper gives summary descriptions of each of the programs. The programs ranged from relatively austere, averaging less than \$4 billion per year, to modestly ambitious, averaging \$6 billion per year. A very ambitious program would have been desirable, but one had not been synthesized at the time this analysis was performed. The first run was made with the original model in which no importance was given to the time of achievement of specific mission objectives. The second run was made with the revised model in which this time of achievement was included. Both of these runs used the numerical values in the correlation matrix directly as averaged from the matrices received from evaluators. There was not a marked difference in results between these first two runs, as may be seen from Figures 2 and 3. The program efficiency function shown in these figures is in terms of worth per dollar, but since

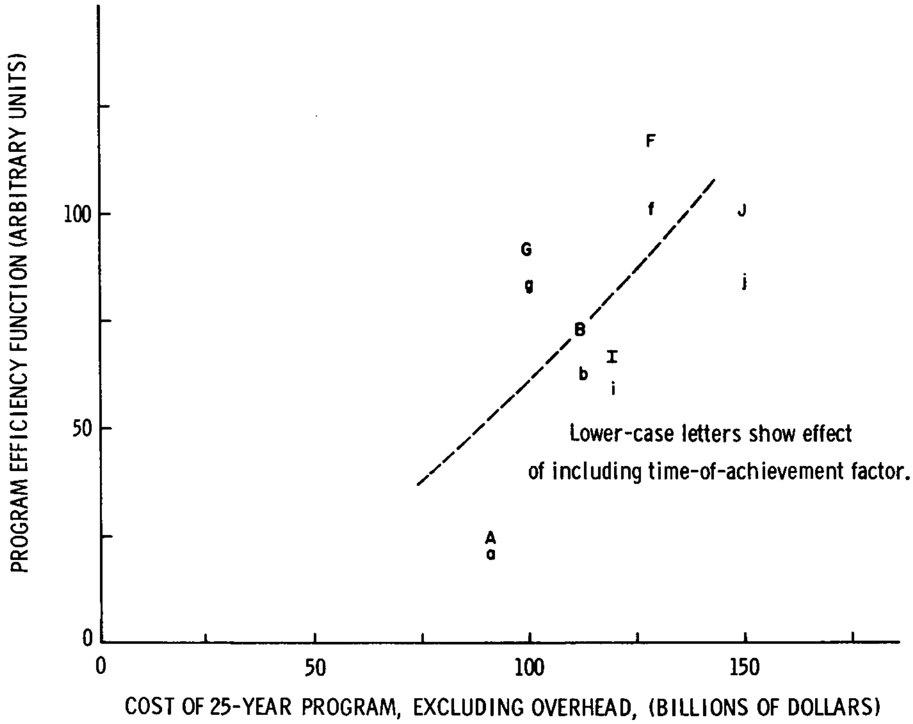

FIGURE 2. PROGRAM COMPARISON

FIGURE 3. PROGRAM WORTH EACH YEAR VS. TIME FOR ALTERNATIVE F

it appears to be always true that a larger program should give more worth per dollar, it is believed to be useful to correlate the efficiency function with the total amount of funding for the program over the given period. Doing this indicates that Alternatives G and F are the most favorable, as is shown by Figure 2. Figure 4 shows worth delivery as a function of time for three of the programs considered reasonably representative. Figure 5 shows overall worth delivery by yield item for Alternative F. From these data certain observations can be made:

1. Alternatives F and G appear to be the best programs.

2. Alternative A is definitely the least efficient program.

3. All alternatives deliver relatively little worth up to the period 1974 to 1975 following which much increased delivery is achieved. This results partly from the fact that this worth analysis was not keyed to the evaluation of existing, approved programs, but rather to evaluation of hypothesized future programs.

4. Alternative J, the most ambitious program, suffers somewhat from erratic delivery of worth and further suffers from having spent large sums of money to develop hardware which was not used effectively in the time period considered.

5. In terms of worth delivery, manned orbital activity greatly overshadows all other activities.

Some discussion is in order regarding this last point.

It is reasonably clear that in the foreseeable future, and within the foreseeable state of the art, that lunar activities will be many times more expensive than Earth orbital activity in terms of payload delivered and man-weeks of experience achieved; and, further, that planetary activities will be again vastly more expensive than lunar activities. Now, if we look at the results of the opinion sampling in the correlation matrix as shown in Figure 1, we find that in those areas where lunar and planetary activity might be expected to be particularly important, viz, in terms of politics and prestige, and in terms of science and technology, they are judged to be more important by only a factor of two to four. The results of the first two runs of this worth analysis, if taken at face value, would indicate that one should put all the money into orbital activity because more ambitious activities such as lunar and planetary are not worth what they cost.

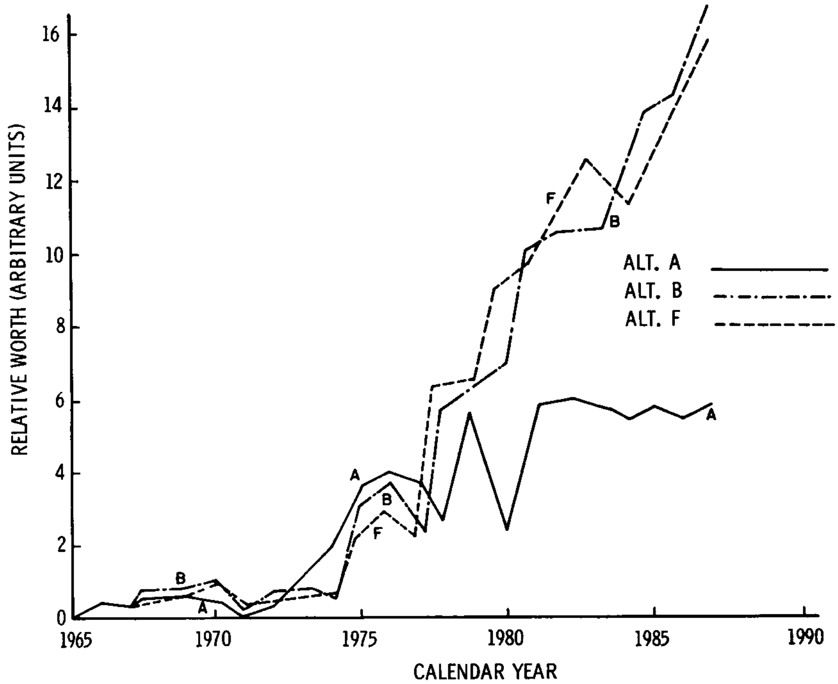

FIGURE 4. PROGRAM WORTH EACH YEAR VS. TIME FOR 3 REPRESENTATIVE ALTERNATIVES

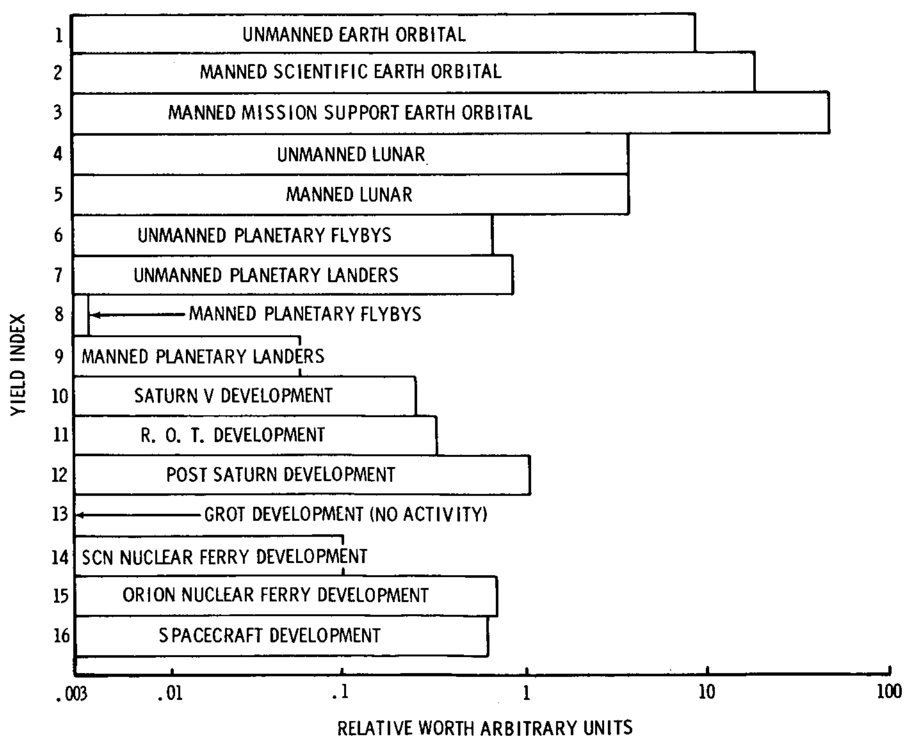

FIGURE 5. PROGRAM WORTH BY YIELD FOR ALTERNATIVE F

There are two ways in which this conclusion might be altered. The first is the use of feedback, wherein those individuals whose opinions are solicited are requested to study the results of the resulting analysis following which they would be asked to vote again. The second uses a rather speculative line of reasoning regarding human nature in making judgments. It is noted that in those areas where quantitative measurements of human response to stimuli have been made, it has been found that the human responds in a logarithmic fashion. If we consider as a base point a sound of 10 db level, then a 20 db sound seems to be twice as loud, and a 40 db sound about 4 times as loud, although the 40 db sound in truth is 1000 times as loud in terms of energy content. A similar logarithmic response is noted for the eye. One may then argue that when quantitative judgments as to relative value are made by people, these judgments should be treated as logarithmic values rather than as linear values. In order to test this hypothesis, the results of the opinion sampling that formed the correlation matrix were revised into logarithmic form by assuming that the numbers in the matrix as originally used represented the logarithm of the weighting factor multiplied by a factor of 100. The values that resulted were then renormalized to sum to the number 1000 in the horizontal direction across the matrix and were used to make another run on the computer.

If this argument is applicable to the correlation matrix it must then also be applicable to the weighting factors associated with the program objectives; therefore, a similar procedure was applied to these objectives except that the original numbers were assumed to represent the logarithm of the weighting factor multiplied by 10 and the resulting values were renormalized to sum to 100.

The results of this manipulation was an almost negligible effect on the relative standings of the various alternatives as shown in Figure 6. Although some alternatives were helped more than others, the new values did not fall outside the range established by the previous two runs. A large part of the reason for the small change was that application of the exponential procedure to the weighting factors for the various objectives resulted in stimulation of the national economy and welfare getting 60 percent of the total weight, and the correlation matrix indicated orbital activity to be of greatest value in satisfying this objective. Thus, Earth orbital activity still proved to be the yield of greatest importance.

Several observations may be made regarding this Worth Analysis Model and the results obtained by its use. If one believes in this method of approach, and if one believes that the inputs used were valid, then one must conclude that the future of space flight as visualized at the present time should lie primarily

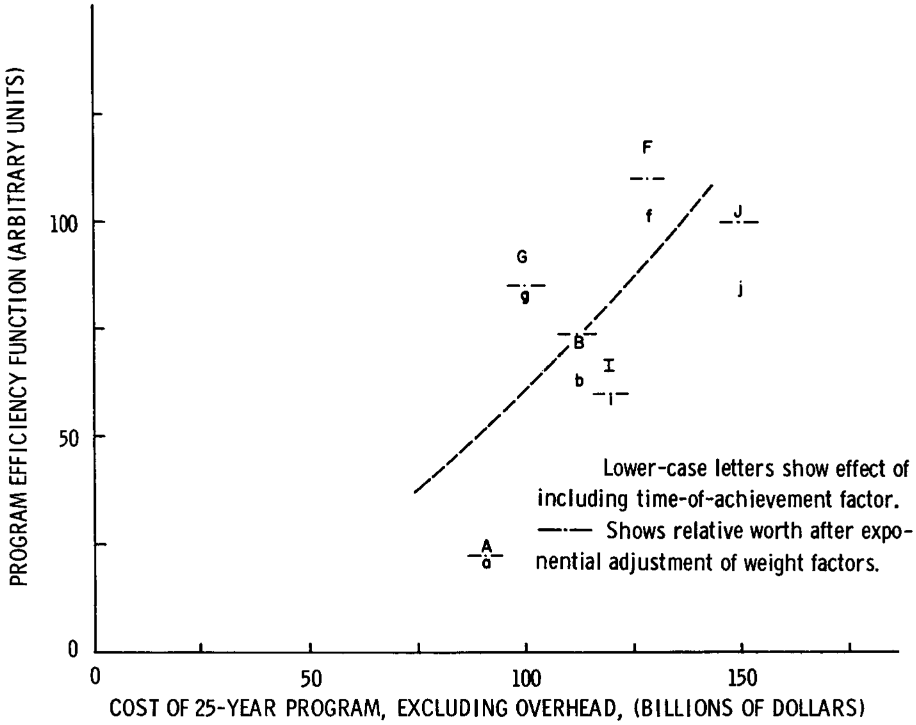

FIGURE 6. PROGRAM COMPARISON WITH ADJUSTMENT OF WEIGHT FACTORS

in Earth orbital activities. Regarding the validity of the inputs, two points should be made. First, a rather small group of individuals made inputs into the correlation matrix. It is doubtful that these individuals gave a great degree of consideration to their value judgments, particularly in regard to relative values between Earth orbital, lunar, and planetary activities. Second, all of the program alternatives used in the analysis were extremely modest in the planetary area. Those alternatives that developed advanced space propulsion capability did not use it for ambitious planetary missions. Although it is true that those alternatives that had more activity in lunar and planetary areas showed up higher on the final rating; the reason that they did so appears to be that these alternatives also had greater Earth orbital activity.

One may also wish to disbelieve the value of the model, and there are possible reasons for doing so. One of the principal ones is the question whether or not the individual, even one who has spent some time thinking about it, can properly weigh the relative value of planetary versus lunar versus orbital activity 20 years from now. They are asked to do this in formulating the correlation matrix. This judgment must actually span the entire time period of the program and, therefore, tends to be very difficult. One may also quarrel with the method of manipulating the inputs because other methods could certainly be chosen, and the one that was used was the result of one man's opinion.

This model is very weak in the area of properly assessing the political worth of the various yield items. The political worth of achieving a milestone first, such as a planetary landing, should be approximately commensurate with the weighting factor given politics and prestige objectives, and should not particularly be a function of the amount of yield achieved in establishing the milestone. This matter of political worth can be readily handled in the type of Worth Analysis Model that uses specific worth estimating equations, because in that type of model, the political worth accorded milestone achievement can be readily adjusted at will by suitably modifying the parameters in the worth estimating equations. The WER (worth estimating relationships) model may be characterized as relying on the judgment of one or a very few individuals who have spent a lot of time analyzing the problem, whereas the matrix model described here may be characterized as relying on the average judgment of a large number of people who have spent much less time thinking about the details of the problem. It is the writer's opinion that the WER type of model can be developed to be more useful and give better results than the opinion matrix model described here; however, it is also the writer's opinion that the opinion matrix model should be available and should be used for comparison purposes.

Both types of models suffer some difficulties with regard to their use in convincing others of the results obtained. One may envision a manager viewing the results of the opinion matrix model and saying, "I like the idea of using opinions from all these different people to get results, but I'm not quite sure I understand what goes on inside that computer program, and I don't know whether I should believe the results or not." On the other hand, one may picture the same individual viewing the results of the WER model and saying, "Well, I imagine that the results you're showing me are the answers you wanted to get, and since you constructed all these worth estimating relations to begin with, naturally the answer that comes out is the one you wanted." It may be added that such an individual could readily be invited to put his own numerical judgments in the opinion matrix rather rapidly, whereas he could certainly not take the time to formulate his own worth estimating relationships. It is the writer's conclusion in this regard that both types of models have considerable value, but that convincing managers (at least those who like to make intuitive seat-of-the-pants judgments) of the value of either one will be a formidable task.

B. PROGRAM SYNTHESIS PROBLEM

One of the ultimate aims of worth analysis applied to space programs would be to synthesize an optimum space program for the nation. The word "optimum" here is used in a very gross sense and it is the writer's opinion that worth analysis, as discussed herein, cannot be expected, by itself, to lead to a so-called optimum program. However, it may prove a valuable tool to those responsible for synthesizing programs for gaining insight into some of the things that influence the apparent worth of a program.

In synthesizing a program one might begin by asking: Are there any projects or activities in space that are essential to national security or survival? Answering this question in detail is beyond the scope of this paper and would, presumably, involve classified information; nonetheless, it represents the first step. Those features of a program, which are essential to national survival or national security, represent the minimum baseline program that is acceptable. Once a plan for the minimum baseline is agreed upon, which is in itself a formidable task, the worth analysis tool may be applied to the problem of deciding which of those "nice to have" features in a space program are actually nice enough to be worth the cost.

The analysis described in detail herein has a serious shortcoming with regard to program synthesis in that it gives no credit for a balanced program with activities in several areas. In the writer's opinion there will be a synergistic effect of interactions of activities in various areas such that the whole will be greater than the sum of its parts. Without such considerations, use of this type of a Worth Analysis Model for synthesis of an optimum program would tend to result in a program with all activity placed in whichever area appears to deliver the most worth, unless several areas deliver roughly equal worth. In that case, the learning curve characteristic would result in the optimum program having activity in several areas.

What would be required of a true program synthesis model? First, it would require the ability, using as an input technical capability versus time, to construct a sample program including all types of activity that might be of interest in the time period considered. Secondly, it would require the ability to select a cost optimum mix of vehicles and systems to accomplish the sample program, including the ability to recognize that if a given vehicle system is not required at all its development costs need not be paid. Thirdly, it would require the ability to utilize a Worth Analysis Model to determine the relative worth of the sample program; and, fourthly, it would require the ability to perturb the sample program in all areas and determine the change in worth for each perturbation thereby performing an iteration process to come up with the best possible program. Finally, it should be able to accept constraints in the nature of budget versus time ceilings and in the nature of essential activities that cannot be eliminated. Such a synthesis model need not necessarily be completely computerized. In fact, with the present degree of understanding of the overall problem, complete computerization would be extremely undesirable since it would probably limit flexibility and further inhibit improved understanding of the overall problem.

APPENDIX

BRIEF DESCRIPTION OF PROGRAM ALTERNATIVES

The following material, abstracted from Future Projects Office working data, describes in summary form the features of the six space program alternatives analyzed in this paper. These programs do not represent NASA forecasts of future space activities; they were formulated by the Future Projects Office merely to be representative of the form which such forecasts might take, and as such are useful in developing program analysis techniques.

A. ALTERNATIVE A

1. Orbital. The orbital portion of Alternative A is constructed to express a maximum Earth orbital program within the constraint of having only one new launch vehicle assumed to be available. This is the Reusable Orbital Transport. The Reusable Orbital Transport is used to rotate personnel and supply all low altitude space stations except the polar orbiting station. The major projects for Alternative A are the manned polar military station, the multipurpose synchronous station, initiated and maintained with 3-stage Saturn V's, the NASA multipurpose R&D station, and the international space station.

2. Lunar. In this alternative, little emphasis is placed on the lunar exploration program. Manned lunar surface operations of minimum activity are planned. The manned lunar orbital operations are programmed to perform extensive photographic surveys and mappings of the lunar surface. The goal of the program is to obtain sufficient physical and geological data to establish the general characteristics and origin of the Moon.

3. Planetary. This plan emphasizes only manned Earth orbital and lunar missions, and appropriates no funds for manned planetary missions. Unmanned planetary probes are nevertheless scheduled, in order to prepare for the manned activity in 1990 and later.

This alternative provides for flyby missions to Venus and Mars from 1965 to 1971, using advanced Mariner, and in 1972 and 1973 using Voyagers. Venus and Mars orbiters in yearly flights and probes to more distant targets are scheduled after 1979. Landers are scheduled to Mars between 1971 and 1979 and to Venus between 1975 and 1989; also flyby attempts to asteroids and comets, about one per year after 1975.

B. ALTERNATIVE B

1. Orbital. This alternative also calls for a maximum Earth orbital program. Three new vehicles are assumed to be available that were not available in Alternative A. These are the Solid Core Nuclear-Orbital Launch Vehicle, the Saturn V tanker, and the Global Range Orbital Transport. The multipurpose synchronous station is delayed until 1979 to make use of the Solid Core Nuclear vehicle that becomes available in 1980, and to conserve funds for the development of the new vehicles. This station is supplied from a lower orbit base that incorporates an Orbital Launch Facility. The Solid Core Nuclear vehicle is the orbital launch vehicle that transfers men and supplies from the lower orbit to the synchronous orbit. Personnel are first transported to the lower orbit with the less expensive and more reliable Reusable Orbital Transport. Two Saturn V tankers refuel the Solid Core Nuclear vehicle for each mission to the higher orbit. The Solid Core Nuclear-Orbital Launch Vehicle is assumed to have a lifetime of six round trips to the synchronous orbit. Three stations are continuously manned in the synchronous orbit and the Solid Core Nuclear-Orbital Launch Vehicle is capable of supplying and rotating crewmen for all three stations on each trip.

2. Lunar. The early years of this program are the same as Alternative A. However, considerably more emphasis on lunar surface operations occurs in the 1980's, because of the availability of the solid-core nuclear propulsion system, This propulsion system is adapted to a lunar ferry vehicle and, with the development of a Reusable Lunar Shuttle, capability for the inexpensive transportation of large payloads to the Moon exists. The additional lunar systems capability in this alternative allows for extensive surface exploration and well founded geophysical and geological experiments. The surface operations are also capable of supporting an astronomical observatory. If necessary, the station can be capable of providing limited support, in the form of emergency communication links, to the manned and unmanned planetary probes.

3. Planetary. Planetary missions obtain some attention in this plan, at the approximately same level with lunar missions; both are secondary in effort and funds to Earth orbital operations. This plan, therefore, allows manned planetary missions. Unmanned missions are carried on in order to facilitate and support the manned missions. There are flybys, orbiters, and landers to Mars, Venus, Mercury, the Asteroids and Comets, as far as feasible. The manned missions, carried on in increasing numbers from 1978 on, comprise Venus and Mars flybys, Venus captures, a Mars capture in 1986, one out-of-ecliptic flight in 1978, and various training flights starting in 1977.

C. ALTERNATIVE F

1. Orbital. Alternative F expresses a minimum Earth orbital subprogram. Therefore, the development of these vehicles is not shown in the orbital subprogram. However, the multipurpose synchronous station, which is probably the most expensive project, is operated in this program, and is supplied with the Solid Core Nuclear - Orbital Launch Vehicle. Also, all of the continuously operating manned space stations are delayed by one to three years to permit funds to be channeled to the lunar subprogram.

2. Lunar. The relatively inexpensive transportation capability in this plan allows the lunar program to achieve the most intensive activity of all other alternatives. Exploration is accelerated and is, therefore, accomplished at an earlier time than for other alternatives. The exploitation phase also starts earlier and is able to reach a much higher manning level than any other alternative.

3. Planetary. In this alternative, funding is excellent for space flight. Although maximum effort is in lunar missions, Earth orbital and planetary missions are nominal. Although the planetary effort is nominal, Earth launch vehicles and orbital launch vehicles are in abundance. Available are Saturn V and tanker, Post-Saturn and tanker, Reusable Orbital Transport, Solid Core Nuclear and Nuclear Pulse vehicles. From the flyby missions beginning in 1977, we are able to go to a Mars landing in 1982, followed by the establishment of a Mars base in 1986. There are unmanned probes every year from 1965 to 1989.

D. ALTERNATIVE G

1. Orbital. Alternative G is a minimum Earth orbital subprogram and is the same as Alternative F except that the synchronous station is eliminated and the Solid Core Nuclear-Orbital Launch Vehicle is not used in the orbital subprogram.

2. Lunar. The lunar program presented in this alternative is much the same as the plan shown in Alternative B. The major transportation modes are programmed exactly the same in the two alternatives. The major difference is actually a second order effect caused by a shift in emphasis on the Earth orbital program between the two plans. The Earth orbital program has maximum emphasis in Alternative B and minimum emphasis in Alternative G. This reduced effort allows the lunar activities to be accelerated in this alternative. The activity does peak out after the early years and is then maintained at a level very nearly the same as that programmed for Alternative B.

3. Planetary. Although the funds are somewhat low, emphasis is on planetary systems, which is nominal, whereas orbital and lunar activity is minimum. Even though the funding is not maximum, we are able to begin flyby missions in 1977. This is due to the minimum activity in orbital and lunar operations. In 1981 there is a Venus capture followed the next year by a Mars landing. A Mars base is established in 1988. The vehicles available in this alternative are Saturn V and tanker, Reusable Orbital Transport and a Solid Core Nuclear vehicle. All years from 1965 - 1989 have unmanned probe activities.

E. ALTERNATIVE I

1. Orbital. Alternative I is a nominal Earth orbital subprogram. The Solid Core Nuclear-Orbital Launch Vehicle, Nuclear Pulse-Orbital Launch Vehicle, and Post-Saturn tanker are also developed in this alternative program. The orbital subprogram for Alternative I is the same as the orbital subprogram of Alternative F.

2. Lunar. The program presented in this alternative represents what is considered to be a plan with nominal emphasis placed on lunar exploration and exploitation. The major transportation modes used are based on the Saturn V and the Post-Saturn launch vehicle. The exploration phase scheduled for this plan is much the same as that presented in Alternative G. However, the exploitation phase is scheduled earlier for this alternative and reaches a more extensive level due to the highly effective Post-Saturn logistics system.

3. Planetary. Although funding is not maximum and orbital, lunar and planetary activity are all nominal, we do have a Post-Saturn and tanker available. We have unmanned probe activity from 1965 - 1989. The first manned flyby mission occurs in 1977. In 1981 we have a Venus capture followed by a Mars landing in 1982 after which there is a lull in anticipation of a Mars base in 1988. In addition to the Post-Saturn and tanker, we have the Saturn V and tanker, the Reusable Orbital Transport and a Solid Core Nuclear vehicle.

F. ALTERNATIVE J

1. Orbital. This subprogram is intended to express a maximum program in all three subprogram areas. For this reason, the orbital subprogram of Alternative J is constructed to be very similar to that of Alternative B. Only minor differences occur between these two alternatives. The Apollo Orbital Research Laboratory synchronous orbit development station is delayed from 1973 to a 1974 launch. Also, the multipurpose large R&D space station is assumed to have a greater frequency of Reusable Orbital Transport resupply launchings than in Alternative B.

2. Lunar. (Same as Alternative F.)

3. Planetary. This alternative has not only maximum funding, but also has maximum activity in the orbital, lunar, and planetary areas. With the funding level of this alternative, we were able to begin the flyby missions in 1975. A Venus capture in 1981 was followed by a Mars landing in 1982. A Mars base was established in 1984, followed by another base in 1986. Vehicles available are Saturn V and tanker, Post-Saturn and tanker, Reusable Orbital Transport, Global Range and Orbital Transport, Solid Core Nuclear and Nuclear Pulse vehicles. Unmanned probe activity was heavy from 1965 - 1989.

Tables A-I through A-IV provide additional data on the six alternatives.

TABLE A-I. MATRIX OF PROGRAM ALTERNATIVES

ALTERNATIVE		A	B	F	G	I	J
EARTH-ORBITAL	MIN				X		
	NOM			X		X	
	MAX	X	X				X
LUNAR	MIN	X					
	NOM		X		X	X	
	MAX			X			X
PLANETARY	MIN		X				
	NOM			X	X	X	
	MAX						X
NEW LAUNCH VEHICLES ASSUMED TO BE AVAILABLE:							
REUSABLE ORBITAL TRANSPORT		X	X	X	X	X	X
POST-SATURN				X		X	X
SOLID CORE NUCLEAR - OLV			X	X	X	X	X
NUCLEAR PULSE - OLV				X			X
SATURN V TANKER			X	X	X	X	X
POST-SATURN TANKER				X		X	X
GLOBAL RANGE AND ORBITAL TRANSPORT			X				X

TABLE A-II. EARTH ORBITAL PROGRAM MILESTONES

MISSIONS	CALENDAR YEAR															
	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83
APOLLO X (30 DAY)	AB J	FG I														
AORL (100-DAY)		AB J	FG I													
AORL (POLAR)			A F G I													
AORL (SYNCHRONOUS)				A			BJ									
LARGE ORBITAL RESEARCH LABORATORY (LORL)						A		B F G IJ								
MULTIPURPOSE SYNCHRONOUS STATION						A						BJ	FI			
SATURN V TANKER DEVELOPMENT									B^3							
POST-SATURN TANKER DEVELOPMENT										F^4 I^4 J^4						
REUSABLE ORBITAL TRANSPORT (ROT) DEVELOPMENT						$A^3 J^1$										
GLOBAL RANGE AND ORBITAL TRANSPORT (GROT) DEVELOPMENT	Notes															B^5 J^5
SOLID CORE NUCLEAR ORBITAL LAUNCH VEHICLE (SCN-OLV) DEVELOPMENT											B^2 F^2 I^2 J^2					

Notes
1. Ist year of development flight - operational in 1975
2. Ist year of development flight - operational in 1980
3. Ist year of development flight - operational in 1980
4. Ist year of development flight - operational in 1980
5. Ist year of development flight - operational in 1985
6. Ist year of development flight - operational in 1985

TABLE A-III. LUNAR PROGRAM MILESTONES

MILESTONES	N/A*	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87
LUNAR ORBITING SURVEY SATELLITE - 3 MEN -		ALL																			
APOLLO-LEM LANDINGS			ALL																		
APOLLO LOGISTICS SUPPORT SYSTEM (ALSS)	F, I,J,				A,B, G,																
MULTI-MISSION MODULE (MMM)	A,			F,J,			G,		B,												
MOLAB-EXTENDED STAYTIME	A,B,			F,J,	I,		G,														
DIRECT FLIGHT PERSONNEL TRANSPORT	A,							F, G,J,		B,	I,										
LUNAR EXPLORATION SYSTEMS FOR APOLLO -CHEMICAL POWER-	A,				F,J,		I,	G,	B,												
LUNAR ORBITING SURVEY SATELLITE -6 MEN-	I								F,J,	A,B, G,											
LUNAR EXPLORATION SYSTEMS FOR APOLLO - NUCLEAR POWER	A,B, G,									I,F, J,											
LUNAR EXPLORATION PHASES																					
A. 30-MAN STATION	A,													B,G,							I,
B. 45 TO 50 - MAN STATION	A, I,													F,J,							B,G,
C. 75-MAN STATION	A,B, G,I,																	F,J,			
D. 100-MAN STATION	A,B, G,I,																				F,J,
REUSABLE ORBITAL TRANSPORT	A,													B,F, J,G,							I,
POST-SATURN	A,B, G,I,													F,J,							
SOLID CORE NUCLEAR FERRY	A,													B,F, J,G,							I,

*MILESTONE NOT ATTEMPTED

NOTE: Dark lines indicate time span during which the various milestones reach operating status.

TABLE A-IV. PLANETARY PROGRAM MILESTONES

		75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
OUT OF ECLIPTIC FLIGHTS			F GT	I		B										
VENUS	FLYBY			J	F G I			B								
VENUS	CAPTURE							G I J			F					B
MARS	FLYBY	J		F G I		B J										
MARS	CAPTURE												B			
MARS	LANDING								F G I J							
MARS	BASE										J		F J		G I	
TRAINING FLIGHTS		J	F G I	B		F IJ	F IJ	F	F	B F J	B F J					

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THE PROBLEM OF SPACE FLIGHT WORTH ANALYSIS

By G. R. Woodcock

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Clasisfication Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

H. H. Koelle

H. H. KOELLE
Director, Future Projects Office

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